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Earthquakes and Mountains Around the Pacific

by Clarence R. Allen

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Clarence R. Allen,

associate professor of geology at the California Institute of Technology, returned last summer from field trips to New Zealand, the Philippines, Formosa, and Chile, to study the dominant fault in each area.

These four faults, plus a big one in Alaska, and the San Andreas in California, are among the major fractures bordering the Pacific. In "Earthquakes and Mountains Around the Pacific," Dr. Allen discusses the unique features of the Pacific earthquake rim.

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Earthquakes and Mountains Around the Pacific

by Clarence R. Allen

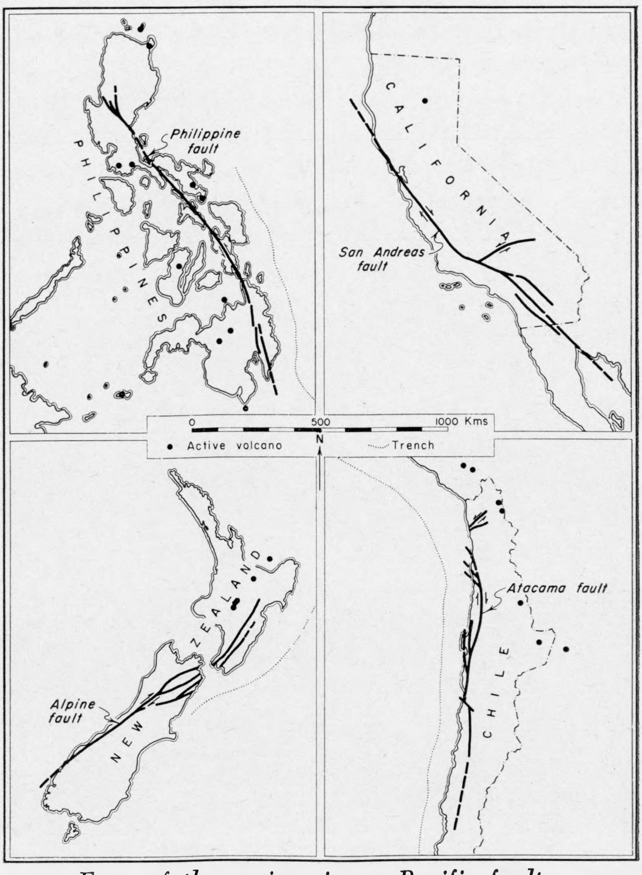
Even after a century of intensive study, the problem of the origin of mountain systems remains as possibly the greatest enigma of the earth sciences. Specifically, what is the origin of mountain-building forces, and how are these forces manifested in the crustal rocks of the earth's surface?

Field geologists who have studied such classical mountain systems as the Alps and the Appalachians have always been impressed by the abundant evidence of uplift and compression shown by the highly deformed rocks in the cores of these ranges; consequently, most theories of mountain building have been intimately concerned with the mechanics of compression and vertical uplift. Contraction of the earth's crust (possibly due to cooling), and thermal convection currents in the earth's interior, are two of the theories most often discussed at present, although they are by no means the only ones.

Geological field studies of ancient mountain systems have told us much about the nature of the associated deformation, and have emphasized some of the conditions and constraints that must be satisfied by any valid theory. If such mountain-building processes are taking place anywhere in the world *today,* however, one might expect to observe them best in the regions bordering the Pacific Ocean, inasmuch as this circum-Pacific "ring of fire" can claim the great majority of the world's current earthquakes, most of its active volcanoes, and most of its very youthful mountain systems.

Great earthquakes certainly represent one of the most obvious manifestations of present-day mountain building, and the 1906 earthquake in San Francisco was one of the earliest circum-Pacific shocks studied in detail. The results were surprising to most geologists, because instead of the associated vertical uplift and evidence of great compression that might have been expected, the ground displacement along the San Andreas fault that caused this earthquake was almost entirely horizontal. During the earthquake, points on the ground surface west of the fault slipped northward as much as six meters relative to points across the San Andreas fault to the east, with little or no vertical offset of the ground surface. Subsequent geological and seismological studies have shown that such horizontal (or "strike-slip") displacements characterize not only faults of the San Francisco area, but most of coastal California and northwestern Mexico as well – throughout the region dominated by the San Andreas fault system. And reconstruction of the geologic history indicates that strike-slip displacement of this type has been occurring intermittently along the San Andreas and associated faults for perhaps as long as 100 million years.

About 20 years ago a large fault system similar to the San Andreas was recognized in another circum-Pacific area — New Zealand. The Alpine fault of southern New Zealand is similar to the



Four of the major circum-Pacific faults.

San Andreas not only in the dominance of horizontal over vertical displacements, but also in that the *sense* of displacement is the same. Both are so-called "right-handed" faults, so that as one faces the fault from either side, the opposite side appears to have moved to the right. Furthermore, the topography associated with the Alpine and San Andreas faults is remarkably similar. Both appear from the air as giant scars or rifts cutting across the landscape, and rivers tend to

Fault trench of Cucapa fault, a branch of the San Andreas, 25 kms south of Mexicali, Baja California.

erode along the faults with anomalously straight courses, owing to the wide zones of crushed and pulverized rocks within the faults.

The predominance of horizontal displacements in California and southern New Zealand did not fit well with existing theories of the mechanism of mountain building, so for many years it was suspected that these two areas were "peculiar" and not typical of the rest of the circum-Pacific belt. There were good independent reasons for this suspicion too. Neither California nor southern New Zealand have the active volcanoes, the deep offshore oceanic trench, or the earthquakes of unusually great focal depth that characterize the more typical circum-Pacific areas such as the Aleutians, Japan, or the west coast of South America; perhaps vertical displacements might still characterize these more typical areas. A few years ago even this idea came under doubt, however, when seismologists found that they could draw certain conclusions about the type of displacement that had caused a given earthquake by examining the seismograph records alone. This technique made it possible to infer the sense of displacement even if the surface effects at the epicenter were concealed by ocean waters or were otherwise unobservable.

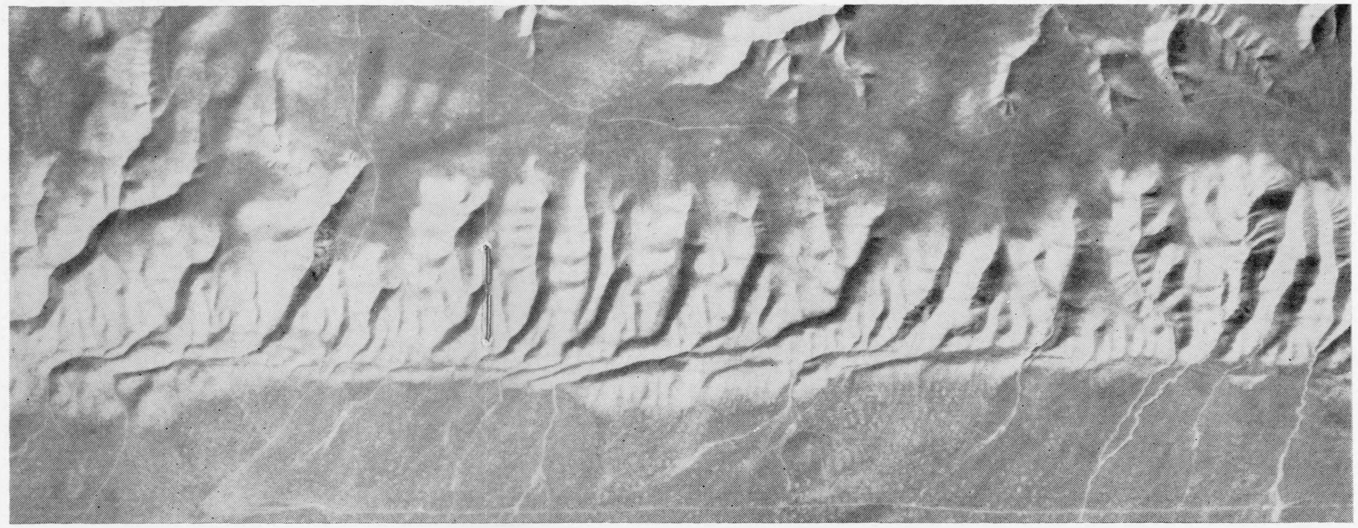
The results of these so-called fault-plane solutions were a great surprise to geologists and seismologists alike, for they indicated that three-quarters of the world's earthquakes were caused by predominantly horizontal fault displacements —not only in California and southern New Zealand, but in almost every other part of the world as well, including the entire circum-Pacific rim. In fact, these results were so startling that there is still spirited scientific debate among seismologists as to whether the method used in the fault-plane solutions is valid. One obvious geological check was to take a closer look at some of the

Wairau Valley, on the South Island of New Zealand, is a fault-controlled valley along the Alpine fault system. The arrows point to scarps of geologically recent breaks.

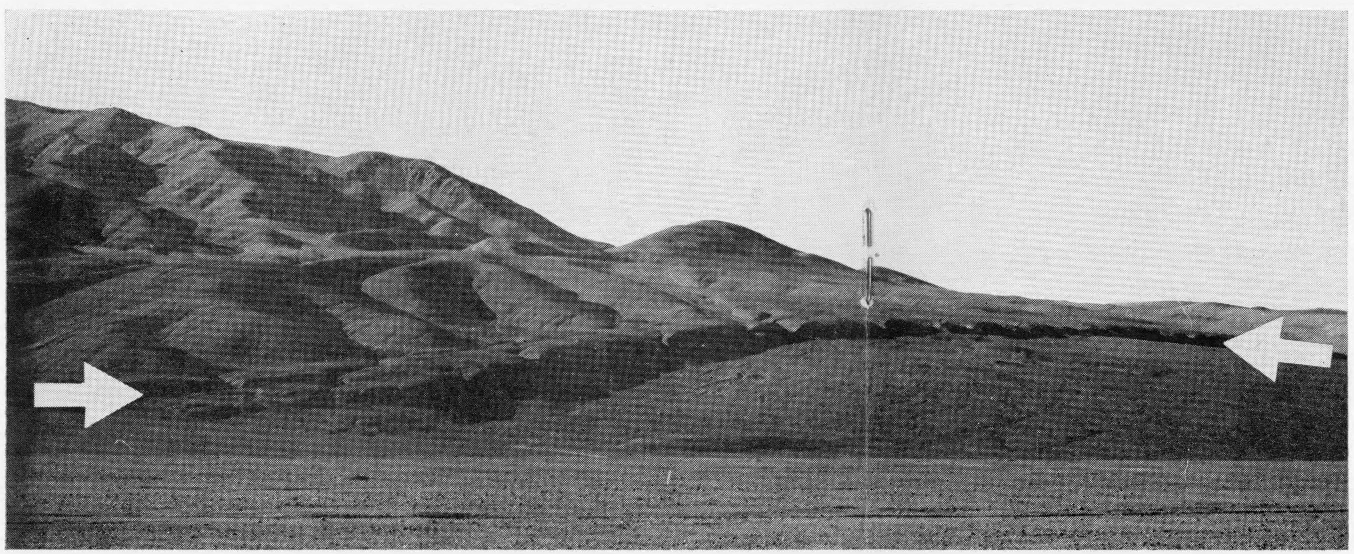
other active circum-Pacific areas to see if faults similar to the San Andreas and Alpine faults might possibly have been overlooked up to this time. An added stimulus was given to this search by the interesting proposal that perhaps the entire Pacific basin was rotating in a counterclockwise direction. This hypothesis was supported by the right-handed displacements parallel to the Pacific margin that had been observed in California, New Zealand, and Alaska, as well as by some of the seismological results. If true, right-handed strike-slip movements should, of course, characterize *all* of the circum-Pacific rim.

Northern Chile is as typical a circum-Pacific area as one could hope to find. It has numerous active volcanoes, a deep offshore oceanic trench, and abundant seismic activity, including earthquakes of very deep focus. Little was known about possible active faulting in this area, and, in 1960, I had the opportunity of working here with Dr. Pierre St. Amand, a Caltech graduate, under the auspices of the Universidad de Chile and the Instituto de Investigaciones Geológicas de Chile. Because of the almost complete absence of rainfall, geological exposures in northern Chile are extraordinary, and our field studies indicated that a major fault zone similar to the San Andreas transects the Atacama Desert of northern Chile for a total distance of more than 1000 kilometers.

Like the San Andreas and Alpine faults, the Atacama fault is parallel to the Pacific rim and gives every indication of a history of horizontal displacement. The fracture is remarkably linear over distances of hundreds of kilometers, which



Aerial photograph of the San Andreas fault 75 kms west of Bakersfield, California. Consistent right-handed offsets of streams crossing the fault reflect horizontal displacements. Length of fault shown is 2.6 kms.



Scarps of the Atacama fault cutting across an alluvial fan near Antofagasta in northern Chile.

Left-handed stream offsets along the Camarones fault, northern Chile. Distance between arrows — 2½ kms.

would be most unlikely if the displacement were predominantly vertical; neither side is consistently higher than the other, yet the disparity in rock types across the fault indicates a significant total displacement; stream channels are offset horizontally where they cross the fault; and giant grooves or "slickensides" on the fracture surfaces are predominantly horizontal where they can be observed in the many mines along the fault. Offset stream patterns and other geologic evidence indicate that the sense of displacement along the Atacama zone has been right-handed. Subsidiary conjugate faults that trend 60° to 90° to the main fault — as in the Camarones fault shown above — are left-handed, as would be expected from mechanical considerations.

Thus the evidence from northern Chile supported not only the idea of worldwide dominance of strike-slip faulting, but was also consistent with the hypothesis of counterclockwise rotation of the Pacific basin. The great earthquake of May 1960 took place much farther south in Chile, and the associated faulting was evidently underwater offshore. However, everything that is known about this earthquake from seismograph records indicates that it, too, was consistent with the rotation hypothesis.

Despite the increasing evidence of strike-slip faulting along the borders of the eastern Pacific, little has been published on the character of possible faults along most of the western Pacific rim. The Philippines looked particularly promising in this regard, because earlier geological work there had indicated the possibility of a major fault zone extending the length of the archipelago from Luzon to Mindanao. Various authors had suggested every different type of displacement on this proposed fault, but had cited rather tenuous evidence. Through the cooperation of the Philippine Bureau of Mines, I had the opportunity to do field work in the Philippines in early 1962, and the Philippine fault turns out to be fully as spectacular in its gross physiographic expression as the San Andreas, Alpine, and Atacama faults, despite the tropical environment. The best exposures of the fault were found on the northern part of the island of Leyte, and the aerial photograph on page 12 shows some features of geologically recent displacements along the fault in this region. This is the area, inci-

Philippine fault zone in northern Leyte. The linear trench is due partly to erosion within the fault zone, partly to recent displacements of the ground surface.

dentally, of perhaps the most intense fighting in the Philippine campaign of World War II. For almost four weeks the opposing armies literally fought for control of scarps of the Philippine fault near the village of Limon.

Determining the sense of displacement along the Philippine fault turned out to be somewhat more difficult than in desert areas such as northern Chile, because the dense jungle cover makes it difficult to identify – either in the field or on aerial photographs – many of the detailed topographic forms caused by recent displacements. However, clear-cut and consistent horizontal stream offsets have now been identified along the fault at numerous localities on the islands of Luzon, Masbate, and Leyte; these offsets are uniformly *left*-handed. Similarly, a great fault parallel to the Pacific margin near the east coast of Taiwan was found to have slipped during a series of major but little-publicized earthquakes in 1951, and in each instance the sense of displacement along the fault was predominantly horizontal and left-handed.

The exposed length of the Philippine fault– over 1200 kilometers – is about the same as that of the San Andreas fault in California and Mexico, and its gently curved trace outlines the arcuate structure of the archipelago. If the Philippine Islands were slightly more submerged, the trace of the fault would be largely concealed beneath the sea, and it seems likely that similar throughgoing faults of strike-slip character underlie many of the other island-arc areas that are less well exposed. Likewise, the 150-kilometer length of fault exposed in eastern Taiwan presumably represents only a short segment of its total length; everything that is known about this fault suggests that it, too, is a master fault of regional tectonic importance.

Thus our field observations in a number of circum-Pacific areas tend to support the viewpoint that strike-slip faulting is indeed the predominant method of seismic strain release in the world today, and that California is not the unique or unusual area that we once thought it might be. But with regard to the question of possible counterclockwise rotation of the Pacific basin, it seems clear that the left-handed displacements that apparently typify the Philippines-Taiwan region are not in harmony with the right-handed displacements that have been observed in Alaska, California, Chile, and New Zealand. The issue is not completely settled, however, because it might still be argued that the true edge of the rotating "disc" is not along the Ryukyu-Taiwan-Philippine lineament, but is instead along the parallel Bonin-Mariana-Palau arc system. I prefer to believe that the pattern of underlying currents is far more complicated than that of a single horizontally rotating disc beneath the entire Pacific, and that considerably more field work will be required before we understand even the basic pattern of deformation.

Where does this leave us with regard to the over-all question of the origin of mountain systems? Indeed, one might well ask: If fault displacements are predominantly horizontal, why should we have mountains at all? Several answers can be suggested:

(1) Certainly not all mountains are fault-bounded; many are associated with regional up-warping, folding, or volcanic activity. In studying faulting and earthquakes, we are obviously dealing with only one mechanism of strain release.

(2) If geologists are right in thinking that the total horizontal displacements on regional faults such as the San Andreas and Alpine may be as much as several hundred kilometers, and there seems to be increasing evidence of this, then a very small departure from purely horizontal movement in any one segment could eventually lead to very significant local vertical relief.

(3) We know very little about what happens at the ends of great strike-slip faults, but it is difficult to avoid the conclusion that considerable stretching and compression of rocks must take place in these areas, with associated vertical adjustments. Likewise, there must be considerable strain in regions where major strike-slip faults change trend, such as near the abrupt bend in the San Andreas fault at the south end of the San Joaquin Valley.

(4) Neither the fault-plane solutions nor field observations of historic earthquakes indicate that *all* earthquakes are caused by predominantly horizontal displacements.

However, the much more difficult question still remains: What is the *mechanism* of mountain building that would lead to predominantly horizontal displacements? It is hard to understand, for example, how this sort of phenomenon could be caused — except locally — by crustal contraction or by convection currents involving turnover of material due to thermal instability in the earth's interior. It would seem instead that we need either some sort of horizontally-moving sub-crustal currents or some mechanism whereby the crust should slip differentially over the underlying materials. One might ask if such displacements could not easily be explained by so-called continental drift, and it is indeed true that the documentation of abundant and large horizontal fault movements adds to the attractiveness of the continental drift hypothesis. But continental drift, even if true, is only a manifestation of more fundamental mountain-building forces and cannot be considered an ultimate cause in itself. So, as of today, the only honest answer we can give in response to the question of the origin of mountain systems is that we simply don't know. And, paradoxically, continuing geological field work, such as our studies of circum-Pacific faulting seems to be making the problem more difficult rather than simpler.

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